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September 7, 1999

New Mexico Range Technical Note No. 87

SUBJECT: **ECS – Publication, "Grazingland Hydrology Issues: Perspectives for the 21st Century"**

Purpose: To correct numbering of the Range Technical Note No. 86.

Filing Instructions: Please pen and ink change for Range Technical Note No. 86 and make it 87 for Publication, "Grazingland Hydrology Issues: Perspectives for the 21st Century."

Number 86 was used twice. Range Technical Note No. 86 should be for the Publication, "Saltcedar (Tamarix spp.) Management with Imazapyr & Restoration of Saltcedar (Tamarix sp. – Infested Floodplains on the Bosque del Apache National Wildlife Refuge."

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August 11, 1999

New Mexico Range Technical Note No. 86

SUBJECT: **ECS – Publication, "Grazingland Hydrology Issues: Perspectives for the 21st Century"**

Purpose: To distribute Range Technical Note No. 86.

Filing Instructions: File attached reference sheet in Range Technical Note II Binder and file publication in Field Office reference library.

The enclosed publication, "*Grazingland Hydrology Issues: Perspectives for the 21st Century*" provides information on grazinglands hydrology that will be useful to field offices, range conservationists, and soil survey offices.

If you require additional information and/or assistance concerning this publication please contact State Rangeland Management Specialist George Chavez at (505)761-4421, Email: fchavez@nm.nrcs.usda.gov.

George Chavez (Acting)

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Attachments

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RANGE TECHNICAL NOTE REFERENCE SHEET

REFERENCE: *"GRAZINGLAND HYDROLOGY ISSUES: PERSPECTIVES FOR THE 21ST CENTURY"*

FILING LOCATION: ______________________________
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PURPOSE: To be used as a tool, guide or reference

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July 20, 1999

NEW MEXICO RANGE TECHNICAL NOTE NO. 86

SUBJECT: **ECS – Publication, "Saltcedar (Tamarix spp.) Management with Imazapyr & Restoration of Saltcedar (Tamarix sp. – Infested Floodplains on the Bosque del Apache National Wildlife Refuge"**

Purpose: To distribute Range Technical Note No. 85

Filing Instructions: File in Range Technical Note II Binder.

The enclosed publications, "Saltcedar (Tamarix spp.) Management with Imazapyr & Restoration of Saltcedar (Tamarix sp. – Infested Floodplains on the Bosque del Apache National Wildlife Refuge" provides information on Saltcedar management and control that will be useful to Field Offices, Range Conservationists, and Soil Survey Offices.

If you require additional information and/or assistance concerning this publication please contact George Chavez, State Rangeland Management Specialist, at (505)761-4421, Email: fchavez@nm.nrcs.usda.gov.

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Weed Technology 1998 Volume 12:345–352

Restoration of Saltcedar (*Tamarix* sp.)-Infested Floodplains on the Bosque del Apache National Wildlife Refuge[1]

JOHN P. TAYLOR and KIRK C. McDANIEL[2]

Abstract: Vegetation development bordering the Middle Rio Grande, as with most major southwestern U.S. tributaries, has historically undergone rapid and dynamic change. The introduction of saltcedar (or Tamarisk, genus *Tamarix*) and other exotic species into this environment within the 20th century has contributed to this process. These plants are now an integral component of the riparian vegetation mix. Manpower, logistics, and financial resources constrain the degree to which a desired riparian habitat can be restored from saltcedar thickets on the Bosque del Apache National Wildlife Refuge near Socorro, NM. Saltcedar clearing is accomplished using a combination of herbicide, burning, and mechanical control techniques costing from $750 to $1,300/ha. Soil salinity and depth to water are the principal physical features limiting revegetation efforts. Cottonwood and black willow plantings and natural regeneration after timed irrigations have produced diverse habitats that support a wide array of faunal species in areas previously occupied by homogeneous saltcedar.
Nomenclature: Saltcedar, *Tamarix ramosissima* Ledeb. #[3] TAARA; cottonwood, *Populus fremontii* S. Wats.; black willow, *Salix nigra* Marsh. # SAXNI.
Additional index words: Phreatophyte control, riparian restoration, Rio Grande, wildlife, imazapyr, *Populus fremontii,* TAARA, SAXNI.
Abbreviations: NWR, National Wildlife Refuge.

INTRODUCTION

Historically, the Rio Grande's narrow riparian corridor, in an otherwise arid environment, has been a rich vegetative mosaic maintained through periodic flooding that fostered patchy habitats with extensive vertical structure. Avian species are the hallmark of this environment and reflect the diverse flora. As with many southwestern river systems, however, habitat degradation has occurred through altered river hydrography and constricted floodplains resulting from irrigation and flood control developments, and the introduction of exotic flora. Resource managers are frequently charged with restoring these riparian habitats with little knowledge of benefits, methodology, costs, and manpower requirements.

In this paper, we discuss efforts by the Bosque del Apache National Wildlife Refuge (NWR) near Socorro, NM, toward rehabilitating saltcedar-infested floodplains and restoring diverse riparian habitats. Efforts to manage saltcedar on the refuge began in the 1940s and continues today. Restoring saltcedar thickets is consistent with the NWR's mission of providing suitable habitats to support a wide array of fauna.

RESTORATION TECHNIQUES

Riparian restoration efforts in the southwestern U.S. began in the 1960s largely supported by federal agencies, including the U.S. Bureau of Reclamation and the U.S. Fish and Wildlife Service, to compensate for river construction and operation projects (Busch et al. 1992). These efforts have varied in scale and have centered on larger river systems, including the lower Colorado River in Arizona and California, the Rio Grande in central New Mexico, and the Salt River in Arizona. Native species revegetation frequently involving preliminary saltcedar control has shown varying degrees of success on impacted sites.

Several methods of saltcedar control have been employed over the last 50 yr. An early method of mechan-

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*. Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

ical removal involved chaining followed by maintenance mowing, but no lasting control was achieved using this method (Great Western Research, Inc. 1989). Annual fall mowing to reduce the stature of saltcedar and to provide a grassland appearance continues today along portions of the Rio Grande, usually within the confines of a levee. Through the late 1940s and early 1950s, various implements pulled by bulldozers and tractors were used for saltcedar control in New Mexico. These included tool bars, root planes, root knives, plows, and saws (Anonymous 1951). In 1960, a root plow pulled by a bulldozer was developed to clear saltcedar stands. The method probably evolved from previously described implements, but was standardized and adopted by river management agencies including the U.S. Bureau of Reclamation. The plow involves cutting the root crown 30 to 45 cm below the surface in dry soil and warm weather (Horton 1960). More than 90% saltcedar control was recorded using this method in early trials, and the technique remains a reliable tool for saltcedar control today. More recently, improved control has been achieved by raking cut stems and roots into piles before burning to prevent sprouting from adventious buds (Bosque del Apache NWR, unpublished data).

Chemical control was used experimentally and later in control maintenance programs during the 1940s and 1950s using 2,4-D [(2,4-dichlorophenoxy)acetic acid], 2,4,5-T [(2,4,5-trichlorophenoxy)acetic acid], and silvex [2-(2,4,5-trichlorophenoxy)propanoic acid] (Anonymous 1951; Bosque del Apache NWR, unpublished data; Busch et al. 1992). These herbicides were generally not effective in killing saltcedar roots, and 2,4,5-T and silvex were banned in 1983 by the Environmental Protection Agency. In the 1980s, new herbicides were found effective to varying degrees for controlling saltcedar. These include triclopyr, which has been most effective as a bark penetrant (Neill 1988), and imazapyr, which is most effective for foliar application (Taylor 1987).

Prolonged flooding has also been used as a means of saltcedar control (Warren and Turner 1975; Widemann and Cross 1978). Seventeen months of prolonged flooding combined with some form of mechanical control, i.e., chaining or plowing, has provided mortality rates near 80%, whereas flooding alone for 28 mo has killed 99% of saltcedar plants. Finally, DeLoach (1989) identified saltcedar as a candidate for biological control. The U.S. Department of Agriculture has approved two species for release, the leaf beetle (*Diorhabda elongata*) and the mealybug (*Trabutina mannipara*), pending an approved biological assessment.

Riparian revegetation techniques have evolved along two lines since the 1970s. The first technique has centered on complete restoration of riparian communities using supplemental irrigation. Anderson and Ohmart (1982) pioneered this technique along the lower Colorado River by installing a drip irrigation system to aid in the establishment of planted materials. Planting prescriptions were based on site capabilities, plant adaptations to soil texture, salinity, depth to water table, and wildlife habitat response models. This restoration effort remains a model of excellence today, as saltcedar thickets have been transformed into native communities maximizing habitat patchiness and vertical flora structure. High cost is the primary drawback to restoration using supplemental irrigation. Costs for projects in Arizona and California have ranged from $864/ha to $1,535/ha, which includes preliminary saltcedar control (Anderson 1988a; Anderson and Ohmart 1982).

A second planting technique utilizes dormant cottonwood and black willow poles augered to the water table to establish forested areas. This technique was first developed for southwestern riparian areas in New Mexico by Swenson and Mullins (1985). In many areas, however, few native stands of cottonwood and willow a[re] available nearby for harvesting poles in large numbers (Busch et al. 1992). Superior stock collections have been gathered by the USDA Plant Materials Center in Los Luna, NM, for eventual release to government agencies for restoration purposes and to nurseries for further propagation (Fenchel et al. 1987). Advances have recently been made propagating coyote willow (*Salix exigua* Nutt.), seepwillow [*Baccharis glutinosa* (R. & P.) Pers.], false indigo (*Amorpha fruticosa* L. #[3] AMHFR), and New Mexico olive (*Forestiera neomexicana* Gray) for use as augered pole plantings (Fenchel et al. 1996). These native shrubs complement several tree species already developed for riparian restoration.

RIPARIAN RESTORATION ON THE BOSQUE DEL APACHE NATIONAL WILDLIFE REFUGE

Between April 13 and 18, 1986, a wildfire consumed 735 ha of riparian habitat on the Bosque del Apache NWR. At the time, this was the largest wildfire ever to occur on the refuge, and it resulted in the destruction of 180 ha of native cottonwood and willow forest habitat. A funding plan to rehabilitate the burned area was [pre]pared and forwarded to U.S. Fish and Wildlife Ser[vice] reviewing officials in June 1986 for submission to the U.S. Department of the Interior for fire rehabilitation funding. This original proposal, based on experimental

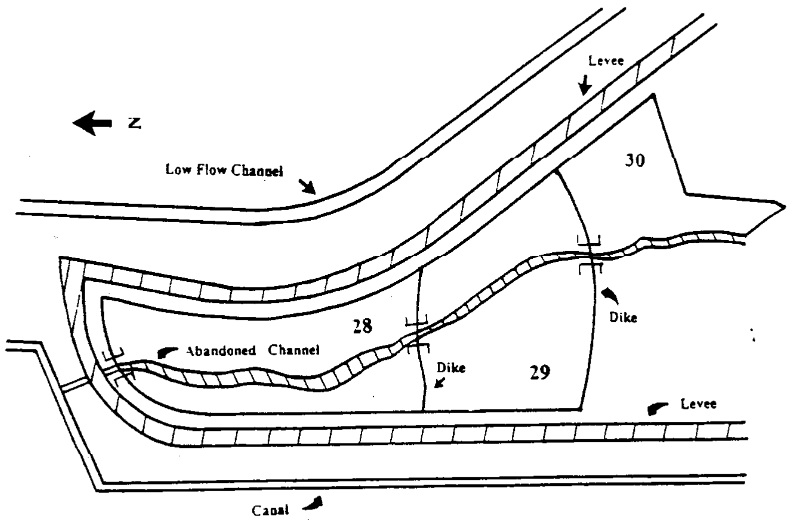

Figure 1. Diagram of landscape features found in the Bosque del Apache, National Wildlife Reserve restoration project area.

restoration work accomplished on the lower Colorado River using drip irrigation (Anderson and Ohmart 1982), totaled almost $1.4 million (Bosque del Apache NWR, unpublished data). The proposal was rejected as too costly, and refuge officials were charged with developing a less costly, yet achievable proposal based on experimental cottonwood and willow pole plantings (Swenson and Mullins 1985).

A second proposal was developed incorporating pole planting with irrigation developments along an abandoned Rio Grande channel in the area. The revised proposal totaled nearly $335,000 and was approved for funding over a 5-yr period from 1987 to 1991. The scope of this project was unique, in that techniques untested on a large scale were used for saltcedar control and revegetation with native species. Today, the project forms a portion of the largest riparian restoration program in the southwestern U.S.

Project Area. The Bosque del Apache NWR encompasses 23,162 ha, of which 3,440 ha are floodplain habitats along a 20-km length of the Rio Grande. The Rio Grande Valley is 5 to 7 km wide through the refuge and is 5.2 km wide at the project site. Low mountain ranges rise 2,000 m to the west and 1,600 m to the east, with valley floor elevations averaging 1,470 m. Woody riparian communities consist of mixed saltcedar/bosque and homogeneous saltcedar thickets. Native species include cottonwood, black willow (*Salix nigra* Marsh # SAXNI), coyote willow, New Mexico olive, false indigo, seepwillow, screwbean mesquite (*Prosopis pubescens* Benth.), wolfberry (*Lycium andersonii* Gray), and fourwing saltbush [*Atriplex canescens* (Pursh) Nuttall # ATXCA]. Understory herbage in cottonwood-dominated areas includes common lambsquarters (*Chenopodium album* L. # CHEAL), narrowleaf globemallow [*Sphaeralcea angustifolia* (Cav.) G. Don # SPHAN], white sweet clover (*Melilotus alba* Medik. # MEUAL), jimsonweed (*Datura stramonium* DC. ex Dunal # DATIN), Virginia groundcherry (*Physalis virginiana* Mill. # PHYLC), silverleaf nightshade (*Solanum elaeagnifolium* Cav. # SOLEL), western ragweed (*Ambrosia psilostachya* DC. # AMBPS), horseweed [*Conyza canadensis* (L.) Crong. # ERICA], and trailing fleabane (*Erigeron flagellaris* Gray) (Ellis et al. 1994). Homogeneous saltcedar communities are generally devoid of herbaceous growth, but some saltgrass [*Distichlis spicata* (L.) Greene # DISSP] occurs in remnant meadows.

The site chosen for restoration is bisected by a Rio Grande channel abandoned in 1942 during the last great flood when the river shifted about 1 km to the east (Figure 1). The area is bordered to the east by a low spoil levee resulting from construction of the Rio Grande low flow channel in the 1960s and on the west by an old levee constructed in the early 1940s prior to the flood. East–west cross dikes were constructed perpendicular to the repaired abandoned channel, separating the project site into three management areas totaling 159 ha. Two areas, units 28 and 29, are 61 ha, while the remaining area, unit 30, is 37 ha. Flood irrigation developments divert water from the main refuge canal to the repaired abandoned channel on the north end of unit 28 with continued flow to units 29 and 30. Water control structures were placed in cross dikes to provide irrigation capabilities and to create wetlands in lower elevations in units 28 and 29.

Table 1. Costs in 1993 dollars related to restoration of saltcedar thickets on the Bosque del Apache National Wildlife Refuge, Socorro, NM.

	Unit 28[a]	Unit 29[b]	Unit 30[c]
		$	
Herbicide application			
Chemical	11.470	8.599	—
Aerial application	1.200	832	—
Resprout maintenance	8.685	501	—
Prescribe burn			
Chaining and fire lines	4.262	—	—
Broadcast burn	1.462	843	—
Mechanical			
Initial aerial clearing	—	—	3.580
Staking and burning aerial debris	5.992	20.220	8.451
Root plowing	8.525	22.141	2.780
Root raking and piling	14.505	19.195	8.645
Debris burning and burying	2.200	4.115	259
Dragging and smoothing	4.618	2.348	4.098
Impoundment/Irrigation development			
Water control structures	5.165	2.530	—
Dike construction	21.645	20.947	—
Site preparation (channeling)	2.486	5.044	—
Site suitability surveys/revegetation			
Topographic survey	660	390	—
Test wells, soil sampling, data analysis	10.588	6.859	5.077
Plant materials	23.000	23.000	2.274
Revegetation	20.696	19.075	13.345
Total	147.089	156.639	48.509

[a] Saltcedar was cleared from 61 ha in unit 28, and 32 ha were revegetated.
[b] Saltcedar was cleared from 61 ha in unit 29, and 29 ha were revegetated.
[c] Saltcedar was cleared from 37 ha in unit 30, and 23 ha were revegetated.

Saltcedar control. Work related to saltcedar control was staggered by unit and began in 1987 on unit 28; in 1988, on unit 29; and in 1991, on unit 30. Both contractor and refuge resources were used with records kept on all costs corresponding to contract equipment and labor prices (Table 1). Prior to clearing, saltcedar canopy closure averaged 70% (±4%) and was not different among units (established from 1987 aerial photos, 2.54 cm = 152 m; 30 random 5-cm measurements per unit). Saltcedar was generally shorter with fewer stems in unit 28 (2.4 ± 0.15 m ht; 4,580 ± stems/ha) than in units 29 and 30 (average, 3.4 ± 0.13 m ht; 7,000 ± 585 stems/ha; measured within 90 random 2.4-m^2 circular plots per unit).

Saltcedar in unit 28 was sprayed in September 1987 by fixed-wing aircraft with imazapyr applied at 1.12 kg/ha in a 140 L/ha solution with a drift control agent and nonionic surfactant added at 0.25% v/v. The next summer, green leaf material was absent and stems were desiccated, so it was decided to chain the standing debris before broadcast burning. Two D-7 class bulldozers dragging a heavy gauge ship chain about 1 m above the surface laid down the standing vegetation in preparation for broadcast burning. Conditions during the burn in September 1988 averaged 40% relative humidity, 25 C air temperature, and 8 km/h wind speed from the south. Fuel moisture content was less than 10%, and the fire consumed over 90% of the woody debris. One year later, saltcedar resprouts were common over most of the burned area. We are not certain, but the high number of resprouts may partially have been the result of incomplete herbicide activity and the fire being conducted too soon after spraying. To control resprouts, the entire 61-ha area was root plowed to a 45-cm depth in autumn 1989 using procedures described by Horton (1960). Roots and other woody debris were then stacked in piles using bulldozers equipped with front-mounted brush blades. After burning and burying the piles, the entire area was smoothed by dragging a rail iron behind a bulldozer in preparation for revegetation. Saltcedar resprouts were still common after root plowing; thus, in August 1990, larger plants were cut and immediately treated with a cut-stump formulation of imazapyr (Chopper®) by ground crews using backpack pump sprayers. In August 1991, remaining resprouts were treated with a foliar application of imazapyr (Arsenal®) applied at 1% v/v in water with a 0.25% nonionic surfactant added to a tank sprayer mounted on an all-terrain vehicle. Estimated cost for saltcedar control on unit 28 was $1,030/ha, which included 2 yr of spot herbicide applications on resprouts In 1995, 6 yr after treatments began, an average of 72 live saltcedar resprouts/ha were recorded after a complete count over the unit.

Saltcedar in unit 29 was initially treated with imazapyr applied at 0.84 kg/ha in a 140 L/ha solution by fixed-wing aircraft in September 1988. Trees were 100% defoliated the next summer, and a broadcast burn was attempted without prior chaining in September 1989. This burn was incomplete; thus, additional aerial vegetation clearing was required. Standing debris was raked at ground surface and windrowed using a hydraulic 6.4-m-wide root rake pulled behind a D-7 bulldozer in autumn 1989. Rake teeth on the implement were 1.2 m in length, spaced 38 cm apart. Windrowed material was consolidated into piles for burning using a 1.9-m^3 capacity scoop articulating loader adapted with a brush rake. As in unit 28, follow-up mechanical control was required over the entire area to reduce resprouts. During summer 1990, unit 29 was root plowed and raked, and debris was stacked into piles. These piles were then burned and the entire area smoothed by dragging a rail iron over the surface. Resprouts were treated in August 1991 with a 1% v/v imazapyr foliar application using an all-terr vehicle. Total cost for this operation was $1,292/ha, a an average of 63 resprouts/ha were counted across the unit in 1995.

From control experiences gained in treating units 28 and 29, it was decided to forego the aerial herbicide application on unit 30 and use mechanical methods as initial treatments. Saltcedar aerial growth was first pushed down with a front-mounted dirt blade attached to a D-7 bulldozer. Debris was stacked with the articulating loader, brush was raked, and piles were burned. Root plowing and root raking followed aerial clearing using equipment and implements previously described. Roots were stacked in piles, burned, and the entire area was smoothed for revegetation using the rail iron dragged over the surface. All work was accomplished over a 6-mo period during spring and summer 1991. Few saltcedar resprouts were found following these control activities, and maintenance spot herbicide applications were not required. Control cost for 37 ha in unit 30 was $750/ha, and saltcedar density averaged 15 resprouts/ha in 1995.

Revegetation. In 1988, five observation wells were hand drilled in unit 28 using a bucket auger and cased in 10-cm PVC pipe, and four additional wells were installed in units 29 and 30. Monitored monthly for 2 yr, the wells indicated water table fluctuations of < 0.6 m, which is ideal for pole planting survival (Swenson and Mullins 1985). Water tables ranged from 1.2 to 4.3 m over the entire project area, but water was generally nearer the surface in the northern portion of the area (unit 28). After saltcedar control work was complete, a 0.2-ha grid system was mapped across each unit, and elevational information was gathered using standard field surveying techniques to determine irrigation zones. Soil samples were taken at the center of each grid, 38 cm below the surface and 38 cm above the water table to determine salinity (electrical conductivity, EC)[4] and soil texture. From this information, a series of contour maps showing salinity levels, depth to water, and elevation were prepared. These maps formed data layers from which grid planting prescriptions were based.

Plantings were made from January to April 1990 and 1991 in units 28 and 29, respectively; and unit 30 in 1992 and 1993. Field crews were provided grid sheets showing the planting prescription based on guidelines developed for optimum survival and growth (Table 2). In retrospect, tolerable salinity levels may have been too high for some species, and the refuge has recently adjusted the original planting guideline given in Table 2. A maximum of 49 cottonwood, black willows, or shrub seedlings were planted in each grid, spaced 6.4 m apart depending on site suitability. For units 28 and 29, propagated and NWR-cut stock was supplied by the Los Lunas Plant Material Center, NM (Fenchel et al. 1987). Tree poles were 2 to 3 m long with 5- to 7-cm butt diam. For unit 30, refuge-grown cottonwood and black willow tree poles were obtained from areas with 3- to 7-yr-old saplings. A two- or three-person refuge crew cutting saplings near the surface harvested about 200 to 300 poles/d. The ends of these poles were soaked in water for 10 d before planting in augured holes that penetrated the water table and left two or three apical branches above the surface on each pole.

Table 2. Prescriptions followed for riparian species plantings on the Bosque del Apache National Wildlife Refuge (NWR), Socorro, NM, from 1989 to 1993.

Species	Soil type	Soil salinity[a]	Depth to water table
Cottonwood	sand–loam	< 3.0	1.8–3.6
Black willow	sand–clayloam	< 4.0	1.2–2.4
New Mexico olive	sand–loam	< 3.0	< 1.2
Skunkbush sumac	sand–loam	< 3.0	< 1.2
Silver buffaloberry	loam–clayloam	< 3.0	< 1.2
Screwbean mesquite	clay–loam	3–8	< 1.2
Wolfberry	sand–loam	3–8	< 1.2
Fourwing saltbush	sand–loam	8–14	< 2.0

[a] Based on experience, the NWR has modified acceptable salinity levels for plantings downward as follows: cottonwood, 1.0 to 2.0 dS/m; black willow, New Mexico olive, skunkbush sumac, and silver buffaloberry, 1.0 to 2.5 dS/m (B. W. Anderson, personal communication).

On average, a three-person crew planted 150 to 180 poles/d using a Texoma production auger (30.5 cm diam) drilling to 4.3-m depth. About 100 to 125 poles/d were planted using a McMillan auger (30.5 cm diam) mounted on a front-end loader bucket drilling to a 3.6-m depth. A Bobcat landscaping machine fitted with an attachable auger (23 cm diam) drilling to 2.4-m depths was the most rapid planting method, as a two-person crew planted 200 to 250 poles/d. Shrubs supplied by the Los Lunas Plant Materials Center were planted in units 28 and 29 but not unit 30 using propagated seedlings in standard book containers with a minimum 20 cm of root development. Holes were drilled to the water table and refilled before planting shrubs to aid root penetration (Anderson 1988b). After hand planting, seedlings were watered from a tank truck and mulched with standard roofing felt as a weed control measure. Seedlings were later flood irrigated about every other month the first growing season and annually thereafter in late May.

Costs for planting 32 ha in unit 28 with 5,500 cottonwood and willow poles and 1,500 shrub seedlings averaged $7.75 per planting. In unit 29, 4,200 cottonwood and willow poles and 2,500 shrub seedlings were planted over 28 ha and cost $7.30 per planting. Costs in unit 30 were lower than in other units because poles were ob-

[4] Soil samples analyzed by the Revegetation and Wildlife Management Center, 201 South Palm Dr., Blythe, CA 92225.

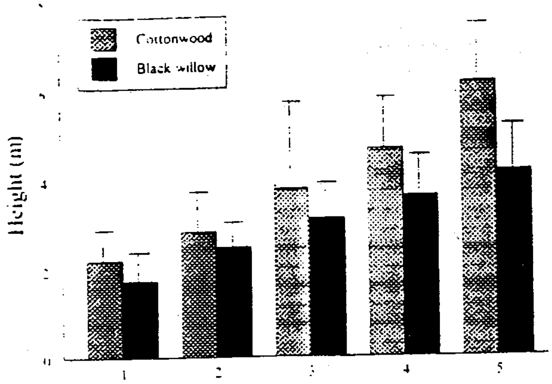

Figure 2. Average annual cottonwood and black willow growth after planting on the Bosque del Apache National Wildlife Reserve, Socorro, NM.

Table 3. Planting survival and natural recruitment 4 yr after revegetation work began on the Bosque del Apache National Wildlife Reserve, Socorro, NM.

	Planting survival		Natural recruitment	
	Unit 28	Unit 29	Unit 28	Unit 29
	%		Plants/ha	
Cottonwood	83	53	33	300
Black willow	81	87	—[a]	367
Wolfberry	30	38	—	—
New Mexico olive	66	49	—	—
Fourwing saltbush	42	0	—	—
Silver buffaloberry	0	—[b]	—	—
Skunkbush sumac	30	19	—	—
Screwbean mesquite	—	40	—	3,400
Coyote willow	—	—	6,300	19,300
Seep willow	—	—	13,500	10,000
Saltcedar	—	—	800	500

[a] No recruitment measured.
[b] Not planted.

tained on the refuge and no shrub seedlings were planted. Crew efficiency also increased, allowing 5,500 cottonwood and black willow poles to be planted on 23 ha for about $3.75 per plant.

Cottonwood survival exceeded 80% 4 yr after planting units 28 and 30, but frost damage shortly after leaf-out in April killed many first-year poles in unit 29 (53% alive after 4 yr). Cottonwood growth was slowed somewhat when poles were planted in areas where water table depth exceeded 4.3 m and soil salinity approached 3.0 dS/m, but overall annual growth was linear and equal across units (Figure 2; height = 1.35 + 0.68 [yr], F = 0.871, df = 2,6, n = 1,032). By comparison, deep tillage to 3 m and drip irrigation for 165 d resulted in 100% cottonwood and black willow survival when plantings were made on a dredge spoil site on the lower Colorado River in Arizona (Anderson and Ohmart 1982). Under drip irrigation, cottonwoods grew about 10 to 15 mm/d during June and July from sites ranging from the Rio Grande near Presidio, TX, to the Kern River in California (Anderson 1989). Black willow established easily in units 28 and 29 (> 80% survival), but the deeper water table and girdling damage by rabbits (*Sylvilagus auduboni* and *Lepus californicus*) to nearly 90% of the first-year trees lowered survival in unit 30 (25% alive after 4 yr). Black willow height increased about 0.75 m/yr through the first 4 yr (height = 1.35 + 0.68 [yr], F = 0.97, df = 2,6, n = 517).

Planted shrub survival, with the exception of New Mexico olive, was disappointing but was more than offset by natural regeneration (Table 3). Native species, including coyote willow, seepwillow, numerous herbs, and, to a certain extent, cottonwood and black willow, responded to irrigations, resulting in nonplanted species comprising nearly 98% of the woody composition in 1995. Considering these results, the refuge now attempts to mimic natural flooding processes using controlled water level manipulations to facilitate regeneration of native flora where possible. Although saltcedar seedlings are recruited using this technique, experience has shown they form a minor component of the overall flora assemblage.

DISCUSSION

Several studies have attempted to compare native riparian vs. saltcedar habitat values for wildlife, but such assessments are difficult, particularly for breeding species (Ellis et al. 1993, 1994; Thompson et al. 1994). By nature, riparian habitats are linear and influenced by zones of transition (edge) from one habitat type to another. Faunal use of edge habitats can be markedly different from more interior homogeneous habitats (Hink and Ohmart 1984), further restricting interpretations from wildlife surveys. Some general conclusions can be drawn, however. Native riparian communities with rich canopy structures and abundant decadent trees that support nest cavities harbor greater species diversity and numbers than saltcedar monocultures (Anderson and Ohmart 1982, 1984; Busch et al. 1992; Ellis 1995; Ohmart et al. 1988; Sedgwick and Knopf 1986). While this statement is usually true in a given area, Hunter et al. (1988) cautions against applying avian use data from one river system to another when assessing habitat values. For example, Anderson and Ohmart (1984) reported lower avian diversity and density in saltcedar habitats than native habitats on the lower Colorado River, yet Raitt and Delasantro (1980) found lower diversity but

Table 4. Faunal richness within a restored riparian area on the Bosque del Apache National Wildlife Refuge (NWR), Socorro, NM.

	Number of species				
Species	1991	1992	1993	1995	1996
Avian[a]	-	25	25	42	59
Small mammal[b]	7	8	7	—	—
Reptile and amphibian[c]	15	9	10	15	19

[a] Avian surveys were conducted during the months of May, August, and September in 1992 and 1993 using the variable circular plot method (Reynolds et al. 1980) and the transect method (Emlen 1971; Franzreb 1981) as described by Stuart et al. (1993) and Stuart and Farley (1994) in units 28 and 29. Surveys were conducted in May, June, and July in 1995 and 1996 using point counts (Bosque del Apache NWR, unpublished data; Ralph et al. 1993) in units 28, 29, and 30. Twenty points were spaced 200 m apart along a 3,900-m transect. Points were visited consecutively from ½ h before sunrise to 1,000 h for a 6-min period.

[b] Small mammal surveys were conducted in June, September, and October in 1991, 1992, 1993 using Sherman live traps as described by Stuart et al. (1992) and Stuart and Farley (1994).

[c] Reptile and amphibian surveys were conducted in June, September, and October in all years. Permanent pitfall-drift arrays (Campbell and Christman 1982) were used in units 28 and 29 in 1991, 1992, and 1993 as described by Stuart et al. (1992) and Stuart and Farley (1994). Permanent pitfall-drift arrays were also used in 1995 and 1996 in units 28, 29, and 30. Arrays were opened for a 9-consecutive-d sampling period per month and checked daily (Bosque del Apache NWR, unpublished data).

higher bird densities in saltcedar habitats along portions of the Middle Rio Grande.

The restoration effort on the 159-ha project area has been instrumental in attracting a diverse fauna. The reactivation of an abandoned river channel through the project area, which in turn provided a water source for wetland development and natural plant regeneration, was perhaps the single most important factor influencing faunal response. Initial site disturbance resulted in abundant seed-producing pioneer herbs that attracted fauna with an affinity to open grassland or shrub habitats. While floral structure and habitat patchiness is still in the early stages of development, a noticeable shift is occurring in the project area toward a wider variety of birds species having various forage guilds (Ellis 1995; Franzreb 1981). Over a 5-yr monitoring period (1992–1996), avian richness nearly doubled (Table 4) (Bosque del Apache NWR, unpublished biomonitoring program data; Stuart and Farley 1994). Compared with other riparian communities, including cottonwood gallery forest and mixed cottonwood forest, the project area now harbors the highest avian species richness of any refuge habitat. Reptile and amphibian species richness is also higher and small mammal diversity on the project area is similar to other nearby riparian habitats on the refuge (Table 4) (Bosque del Apache NWR, unpublished data; Ellis et al. 1993, 1994; Stuart et al. 1992, 1993; Stuart and Farley 1994). Developing flora and progressively more mesic microhabitats reflected a general shift from fauna typical of dryer, less densely vegetated habitats to species representing more mesic fringes.

In terms of faunal response, there is no question that restoration on the project area has been worthwhile. The high cost of this effort, however, cannot be overlooked (Table 1). The least expensive mechanical saltcedar control cost was $752/ha in 1993 dollars, which is similar to mechanical clearing on the Cibola NWR in Arizona at $775/ha in 1982 dollars (Anderson and Ohmart 1982). Revegetation costs were nearly twice as high when both seedlings and poles were planted from nursery stock compared to use of locally harvested plant materials. Planted areas do not capture the full scope of restoration work that occurred during the project, however. By providing irrigation capabilities, wetlands were developed in areas unsuitable for planting, which enabled recruitment of native flora through natural regeneration.

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Saltcedar (*Tamarix* spp.) Management with Imazapyr[1]

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Abstract: During the 20th century, naturalized saltcedar has become common within major tributaries throughout the western United States. Often growing in nearly monocultural stands, saltcedar is suspected of lowering water tables, thus destroying wetlands and wildlife habitats. Management efforts have primarily relied on mechanical and cultural practices, but recent success in controlling saltcedar with imazapyr has led to wider herbicide use. Based on a number of research/extension field trials in New Mexico from 1987 to present, imazapyr applied alone or in combination with glyphosate was found to control saltcedar to levels of 90% or greater, especially when applied in August or September. For fixed-wing aircraft applications, we recommend applying imazapyr at 1.1 kg ai/ha or imazapyr plus glyphosate at 0.56 plus 0.56 kg/ha. For individual plant treatments, we recommend spraying the foliage to wet with imazapyr at 1% v/v in water, or imazapyr plus glyphosate at 0.5 plus 0.5% v/v. Herbicide activity may be reduced as saltcedar height and stem number increases.

Nomenclature: Glyphosate, *N*-(phosphonomethyl)glycine; imazapyr, (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid; saltcedar, *Tamarix ramosissima* Ledeb. #[3] TAARA.

Additional index words: Aerial application, cultural control, ground application, mechanical control, phreatophyte, arsenal, glyphosate, triclopyr, 2,4-D, TAARA.

Abbreviations: NWR, National Wildlife Refuge; PRNRRP, Pecos River Nature Riparian Restoration Project.

INTRODUCTION

Interest in saltcedar (or Tamarisk, genus *Tamarix*) has been especially keen in the 1990s, and several symposia and papers have addressed its biology and control. To gain a historical perspective on saltcedar management, the reader is referred to several extensive literature reviews (Brock 1994; Brotherson and Field 1987; DeLoach 1991; Frasier and Johnsen 1991; Graf 1982; Horton 1977; Horton et al. 1960; Kerpez and Smith 1987; Robinson 1965). Proceedings from various riparian conferences also include valuable discussions on saltcedar (Clary et al. 1991; de Waal et al. 1994; di Tomaso and Bell 1996; Finch and Tainter 1995; Kuntzman et al. 1987; Tellman et al. 1993; Warner and Hendrix 1984). Case histories describing efforts to control saltcedar are numerous, and accounts describing successes and failures are easy to find (e.g., Kerpez and Smith 1987; Lovich et al. 1994). In most instances, efforts that have taken advantage of local conditions and used a multitude of practices over long periods of time have brought some measure of success in controlling saltcedar. Single-treatment approaches have proven impractical because no method completely eliminates mature saltcedar and its later progeny. Though saltcedar is an exotic weed in the U.S., it must now be regarded as a permanent resident. If saltcedar control is to be successful, management approaches must consider the ecological niche the plant has carved for itself over the past century, both in and outside riparian systems.

In this paper, we emphasize current and potential developments for managing saltcedar with herbicides. Comprehensive literature reviews describing saltcedar control by biological, fire, mechanical, and chemical techniques are contained in Brock (1994), DeLoach (1991), and DeLoach et al. (1996). Control measures in river channels, such as flooding and inundation, are described by Graf (1978, 1979, 1982) and Great Western

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

Research, Inc. (1989). We focus much of our discussion on relatively recent experiences with saltcedar control in New Mexico using imazapyr and other herbicides. Saltcedar efficacy results presented herein have been provided in local extension and research related reports, but results are not generally available outside New Mexico.

SALTCEDAR—THE PROBLEM

The name "saltcedar" is probably derived from the salty residue that collects on the small, scalelike leaves that resembles cedar foliage (Bowser 1957). More than 50 species of *Tamarix* have been described worldwide (Baum 1978), with four of these commonly referred to in North America as saltcedar: *T. gallica* L., *T. pentandra* Pall., *T. ramosissima* Ledeb., and *T. chinensis* Lour. (Frasier and Johnsen 1991). The 1989 *Composite List of Weeds* of The Weed Science Society lists only *T. ramosissima* as saltcedar and provides different common names for the other species. However, ecological and taxonomic similarities in these species make separation in the field extremely difficult. Thus, for practical reasons, all species are collectively treated here as one, as they are in most ecological studies (Everitt 1980).

Saltcedar accessions from southern Europe, northern Africa, and eastern Asia were first advertised in horticultural catalogs for ornamental sale in the United States in the 1820s (Frasier and Johnsen 1991). It was sold in California in nurseries in 1856 and was available from The National Arboretum by 1868 (Allred 1996). Early plantings escaped cultivation, and by the late 1800s, saltcedar was naturalized along many rivers and streams throughout the southwestern U.S. (Robinson 1965). Some have claimed saltcedar was present in New Mexico by the mid-1800s (Emory 1948:200, footnote 55), but extensive botanical explorations by New Mexico botanist E. O. Wooton from 1890 through 1910 failed to document the plant (Allred 1996). In the early 1900s, private landowners and government agencies purposely planted saltcedar for streambank erosion protection and as windbreaks (Watson 1912). In 1925, an article in the *New Mexico Extension News* reported a plan to plant saltcedar at the head of arroyos above Silver City, NM, in an attempt to slow overland water flow and to reduce soil erosion. The article described how saltcedar plantings in the upper reaches of the Pecos River above Lake Millan reservoir had "successfully spread," making it impossible for a flood to wash out streambanks. Saltcedar in the McMillan Delta area covered 240 ha in 1915 and from this nucleus spread up and down the Pecos River. By 1925, saltcedar covered 5,000 ha; by 1946, 10,600 ha; by 1955, 16,500 ha; and by 1960, about 20,000 ha (Robinson 1965). Recent estimates of saltcedar occupation along the Pecos River are near 120,000 ha (Brown et al. 1993).

The spread of saltcedar throughout the western U.S. has been documented by Robinson (1965), Harris (1966), and more recently by Brock (1994). There is general agreement that, with the completion of large reservoirs on most major rivers, the saltcedar invasion has now peaked. Graf (1982) examined ground and aerial photographs taken from the late 1800s to 1979 to describe changes in saltcedar cover through time from selected portions of the Salt and Gila rivers in central Arizona. Graf (1982) reported saltcedar increased dramatically from when it first appeared, in the early 1890s, until 1941, when dense thickets posed serious flood control problems by reducing the capacities of major channels. From 1941 to 1979, the total area of saltcedar in the channels of the Salt and Gila rivers from Granite Reef Dam to Gillespie Dam declined by nearly 53% (4,900 to 2,300 ha). Graf (1982) attributed the reduction in saltcedar thickets to a continual lowering of the water table by groundwater pumping, conversion of land to agriculture, and to upstream flood control works built t limit flood flows.

Since its introduction, saltcedar has continued to expand its range, if not its areal extent, into the upper reaches of many western waterways. New occurrences continue to be recognized in previously unreported areas, suggesting it has not yet reached its eventual distribution range. Brock (1994) prepared a map showing the distribution of saltcedar along major tributaries in the western U.S. and agreed with other scientists (Bowser 1957; Gesink et al. 1970; Lindwauer 1967, among others) that its abundance, and perhaps its distribution, is influenced most greatly in channel reaches by temperature. Bowser (1957) reported saltcedar not to spread rapidly above 1,220 m, although it is present at elevations up to 3,350 m. Brock (1994) agreed with this observation for Arizona, but dense thickets occur at close to 1,500 m above Elephant Butte Reservoir on the Middle Rio Grande near Socorro, NM.

Prior disturbance and depth to water table largely dictate if saltcedar grows into a single stemmed tree with a bole up to 0.5 m in diameter and a height of 11 m, or as a low growing, multistemmed shrub. On the Bosque del Apache National Wildlife Refuge (NWR) near Socorro, NM, saltcedar thickets are periodically burned wildfires. On one such area, where the water table is < 3 m from the surface and saltcedar was burned to the ground 3 yr earlier, tree densities were 7,118 plants/ha with an average height of 2.3 m, 32 stems/plant, and 56% cover (K. C. McDaniel, unpublished data). Where the water table is deeper than 6 m from the surface, saltcedar takes an open, savannahlike form, with 4 to 6 m between plants.

A single saltcedar plant growing in the open produces as many as 500,000 seeds in a growing season that extends from April to October (Warren and Turner 1975). Seed dispersed by wind and water germinates within 24 h of wetting when deposited on moist soil (Everitt 1980). Warren and Turner (1975) found a viable seed density of 17/cm^2 on an Arizona mudflat. They reported that seed remains viable up to 5 wk under normal storage conditions, but can survive up to 1 yr in cold storage.

Nearly 100% of saltcedar stems and root cuttings sprout at all times of the year, provided they are kept warm and moist (Horton et al. 1960). After burning, mowing, or other top growth removal, sprouts from the crown grow up to 4 m in 1 yr. Similarly, top growth suppression by certain herbicides, such as 2,4-D [(2,4-dichlorophenoxy)acetic acid] or glyphosate [*N*-(phosphonomethyl)glycine], defoliate a plant for a growing season, but because the root system is not usually killed, the plant often appears unsprayed in 2 or 3 yr.

NEW MEXICO SITUATION

Saltcedar management in New Mexico during the 20th century can be divided into three distinct phases. From 1900 to the early 1940s, saltcedar expansion into major tributaries was rampant and largely unchecked. Problems with saltcedar growing in channels was well recognized during the 1940s to mid-1970s, and various land clearing and water management efforts to remove saltcedar were employed by irrigation districts, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and other authorities (Anonymous 1951; Hollingsworth 1973). The primary goals for manipulating saltcedar-infested channels were: (1) to facilitate water transport, (2) to reduce flood and surface flow, (3) to reduce sedimentation, and (4) to enhance irrigation return flows (Graf 1978). In some instances, saltcedar removal was justified for recreational purposes and as a benefit for wildlife habitat improvement (Kerpez and Smith 1987). Manipulating saltcedar for the purpose of providing diverse riparian growth was usually not a primary consideration. During the early 1980s, emphasis on land conversion began to diminish because of public concerns and questions about the cost and ecological value of such practices. Further, the resource value of riparian areas was recognized and the optimization of a single-return product, such as increasing water yield, could no longer be used as the sole justification for management. Management of many saltcedar-infested floodplains along southwestern rivers is now characterized by a comprehensive approach that attempts to suppress saltcedar spread and to restore the perceived natural riparian vegetation.

In the 1960s to mid-1970s, under the supervision of the U.S. Bureau of Reclamation, silvex [2-(2,4,5-trichlorophenoxy)propanoic acid] and other herbicides were aerially sprayed on saltcedar-infested areas along portions of the Rio Grande and Pecos rivers. Sprayed annually or every few years, silvex provided growth suppression, but few trees were killed. Broadcast herbicide spraying ceased even before label cancellation of this product in 1983. In recent years, interest in the use of herbicides for saltcedar removal has increased, both for the reasons listed above by Graf (1978) and Kerpez and Smith (1987), but also as an initial step in the process of restoring riparian vegetation. Numerous herbicides for saltcedar control have been examined in research trials, but until recently, few have been used commercially on a wide scale. In general, phenoxy herbicides such as triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid) and 2,4-D have continually been used for saltcedar control on an individual plant basis, but aerial broadcast began only when imazapyr was registered for this use in the late 1980s.

In New Mexico, aerial and individual plant field trials using imazapyr and other herbicides have been applied since 1987 by various agencies and chemical companies as well as by New Mexico State University. Many of the herbicide trials reported herein were not established strictly for research purposes, but do provide a valuable comparison of different herbicide rates and formulations. Data describing site conditions, size of trees, associated vegetation, and environmental conditions when sprayed were included to develop treatment recommendations and to identify areas where further research might be required.

HERBICIDE TRIALS

Individual Plant Trials. Researchers began field trials with imazapyr and other herbicides in 1987 to develop Extension Service recommendations for herbicide control of saltcedar. These research/demonstration trials were rarely replicated, except by location, and were not designed for statistical analysis. However, they provided useful information on the timing of application and de-

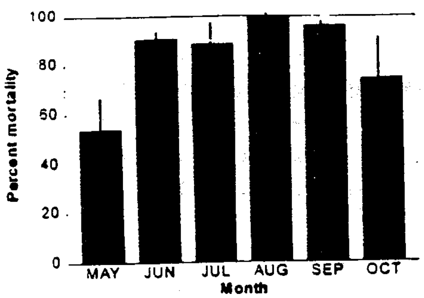

Figure 1. Mean saltcedar mortality with standard error by month of treatment across all sites and years for a 1.0% solution of imazapyr foliar applied to individual plants in New Mexico, 1987–1994.

gree of control that might be anticipated using a particular herbicide. Many of the trials were repeated at the same location for 3 or more yr. Foliar spray trials were applied with either a backpack or a trailer-mounted power sprayer. Plot size was usually determined by the number of trees that could be sprayed with one tank of solution. Tree size was the determinate factor in the number sprayed per plot, but usually 25 or more trees were treated. Saltcedar mortality was determined at 3 yr after treatment by counting the number of dead plants in each plot and dividing by the total number of plants. Mortality rates were combined by rate across all sites for the purpose of this paper. Individual site mortality data are reported annually in NMSU Agricultural Experiment Station Range Brush Control Reports (Duncan and McDaniel 1996a). Liquid herbicides were always mixed in water with a 0.25% v/v nonionic surfactant and sprayed to wet foliage, but not drip. Particular attention was paid to spray terminal ends of all branches, including blooms. The interiors of plants were then laced with the spray solution to complete treatments.

Imazapyr was applied alone in earlier trials, but beginning in 1990, mixtures with glyphosate were compared. The practical advantage of an imazapyr–glyphosate combination is cost: formulated imazapyr (Arsenal®) cost nearly three times more than formulated glyphosate (Rodeo® or Roundup®). Results from individual plant trials indicated imazapyr at 1% v/v or imazapyr plus glyphosate applied at 0.5 plus 0.5% v/v usually provided more than 90% saltcedar mortality, irrespective of spray date. In eight of nine trials when saltcedar was sprayed in August and September, mortality was at least 99% when sprayed with the 1% v/v imazapyr rate (Figure 1). Control usually was lower when saltcedar was sprayed early (April) or late (October) in the growing season. Herbicide efficacy was rarely better when higher concentrations of imazapyr or imazapyr plus glyphosate were added to the spray solution. Glyphosate applied alone as a 2% v/v solution provided only 32% saltcedar mortality, indicating the necessity of adding imazapyr to glyphosate mixtures.

Experiences gained from these trials led to the development of guidelines for saltcedar control on an individual plant treatment (IPT) basis in New Mexico (Duncan and McDaniel 1996b). These guidelines include: (1) treat young or regrowth saltcedar because plants under 4 m in height are more easily sprayed and controlled than taller trees, (2) treat areas previously root plowed, mowed, or cleared, or areas where saltcedar appears to be newly invading, (3) treat areas with tree densities of fewer than 400 plants\ha, (4) although the optimum tank mix solution for imazapyr plus glyphosate has not been developed, a 0.5 plus 0.5% v/v combination with water and a 0.25% v/v nonionic surfactant gives results comparable to imazapyr applied alone in a 1% v/v solution, and (5) spray foliage to wet, especially terminal ends of all branches. Allow two full growing seasons before follow-up management.

Carpet Roller Trials. Two trials were conducted with a farm tractor (27 horsepower) bearing a hydraulic front-mounted implement fitted with a carpet-covered drum to apply herbicide to low growing (< 3 m tall) saltcedar saplings. Herbicide solutions were sprayed onto the surface of the revolving carpet, which then wiped the chemical onto the foliage (Mayeux and Crane 1983). Herbicide solutions applied with the carpet roller at 0.125% imazapyr or 0.125% plus 0.125% v/v imazapyr plus glyphosate resulted in 92 and 85% mortality, respectively. Apparent mortality dropped to 32% for imazapyr plus glyphosate applied at 0.1% plus 0.1% v/v. Glyphosate applied alone at 0.5% v/v resulted in only 5% mortality, while imazapyr applied alone at 0.25% v/v resulted in 94% mortality 2 yr after application.

The carpet roller wiped the herbicide solution directly onto contacted plants without touching understory vegetation or bare ground. This has an advantage, because both imazapyr and glyphosate are nonselective and capable of damaging or killing desired vegetation. Vallentine (1989) suggested carpet roller treatments to reduce the amount of herbicide introduced into the environment, which in turn reduces application costs. One problem found in New Mexico with carpet rollers was the presence of obviously untreated plants. This may have been the result of operator inexperience, as more untreated plants were encountered in plots treated first than those treated later. As the tractor operator became more experienced with the operation of the carpet roller, the incidence of untreated plants declined.

Aerial Herbicide Trials. The first reported aerial broadcast of imazapyr was made at a 1.12 kg ai/ha rate to a near-monocultural stand of saltcedar about 50 ha in size on the Bosque del Apache NWR along the Rio Grande near Socorro, NM, in August 1987. Saltcedar sprayed was 3 to 7 m in height, multistemmed, and formed a near-closed canopy. The commercial agricultural aircraft was calibrated to deliver a high volume of spray solution (140 L/ha) for better penetration into the dense canopy. In summer 1988, it was obvious the treatment damaged saltcedar, as little live leaf or stem material remained. A second nearby area was sprayed on the Bosque del Apache NWR in August 1988 using the same aircraft and spray volume but a reduced rate of imazapyr (0.84 kg ai/ha). In summer 1989, more regrowth appeared on lower branches and from the root crown of defoliated saltcedar sprayed in 1988 compared to 1987, suggesting the trees were responsive to dosage rate. In August 1989, a 10-ha saltcedar thicket near Artesia, NM, was aerially sprayed with imazapyr at 1.12 kg/ha. First-year results were comparable to those observed after the 1987 Bosque del Apache NWR spraying. Three years after treatment, saltcedar mortality was about 95% on both areas. These initial experiences indicated the potential for saltcedar control with imazapyr, but the optimum rate and the potential for mixing more economical combinations with glyphosate were not defined.

In September 1992, a helicopter fitted with a 9-m spray boom applied imazapyr and imazapyr plus glyphosate solutions to 2- or 10-ha-sized plots with saltcedar growing along the Pecos River near Artesia. Results were inconsistent, as herbicide efficacy across treatments ranged from 31 to 90% with no clear rate response detected. Imazapyr applied at 1.12 kg/ha resulted in the highest saltcedar mortality at 90%. Tank mixes of 0.56 kg/ha imazapyr plus glyphosate at up to 3.36 kg/ha provided less than 85% saltcedar mortality 3 yr after treatment. Glyphosate at 8.8 kg/ha provided only 30% saltcedar mortality. The required high spray volume (93 L/ha) coupled with a small mixing tank capacity and a narrow spray swath led to poor herbicide coverage, which resulted in heavy streaking. Mortality data for the helicopter trial were obtained by counting 200 plants within the nonstreaked portion of the study.

Comparative herbicide trials with a fixed-wing aircraft began in 1993 and 1994 near Artesia. These applications provided more uniform herbicide coverage than those made by helicopter. Imazapyr applied at 0.84 kg/ha provided higher saltcedar mortality in 1993 (79%) than in 1994 (66%), but imazapyr plus glyphosate combinations provided similar efficacy results both years (Table 1). Interestingly, imazapyr plus glyphosate at 0.42 plus 0.42 kg/ha controlled about the same percentage of saltcedar (roughly 80%) as imazapyr alone at 0.84 kg/ha. There was a definite imazapyr rate response indicated, especially when the glyphosate rate was held constant at 0.56 kg/ha. Data shown in Table 1 are results from the aircraft fitted with conventional raindrop nozzles delivering a 65 L/ha spray volume. When micronaire nozzles spraying 28 L/ha total volume were compared to raindrop nozzles at the same rate, a 10 to 15% higher mortality resulted with the use of raindrop nozzles (data not shown). Saltcedar mortality was determined by counting 200 plants within each plot 2 yr after treatment.

Table 1. Average saltcedar mortality 2 yr after fixed-wing aircraft herbicide applications near Artesia, NM, in 1993 and 1994.

Herbicide	Rate	Saltcedar mortality by year	
		1993	1994
	kg/ha	%	
Imazapyr	0.84	79[a]	66
Imazapyr + glyphosate	0.28 + 0.56	65	61
	0.42 + 0.42	80	81
	0.42 + 0.56	71	79
	0.56 + 0.56	87	87

[a] Mortality determined by plant count (200) within each plot.

In 1995, evaluations were taken of the 1993 and 1994 aircraft plots to determine herbicide effects on different size classes of trees (Table 2) (Noffke 1996). Four equally spaced belt transects (5 by 50 m) placed parallel to the flight path in each treatment were used to measure tree height, stem numbers, and mortality for saltcedar within belts. Trees were divided into one of five arbitrary height classes (< 3, 3, 4, 5, or ≥ 6 m) and four stem classes (1 to 4, 5 to 9, 10 to 19, and ≥ 20 stems per plant) to compare mortality data. Analysis of tree size data using PROC GLM and PROC FREQ statements in SAS (SAS 1988) indicated the growth form of the plant influenced herbicide efficacy. In general, taller trees were more resistant to herbicide applications than shorter trees, and trees with a high number of stems were more resistant than trees with fewer stems.

PECOS RIVER RESTORATION PROJECT

As a practical application of experiences gained from research/extension demonstration efforts, the Pecos River Native Riparian Restoration Project (PRNRRP) was begun in 1994 using aerial/ground herbicide applications as the initial intervention step for removing saltcedar. The goal of the project is to reestablish the native ripar-

Table 2. Average saltcedar mortality by stem and height classes, irrespective of herbicide type, 2 yr after fixed-wing aircraft applications near Artesia, NM, in 1993 and 1994

Height class	Stem class by year sprayed (stems/plant)								
	1993				1994				
	1–4	5–9	10–19	$\bar{x}$[a]	1–4	5–9	10–19	≥ 20	$\bar{x}$[a]
m	No./plant								
< 3	—[b]	75	100	67 ab	100	82	84	100	86 a
3–4	83	76	50	74 a	63	81	78	73	77 ab
4–5	75	68	44	66 ab	90	77	67	47	69 bc
5–6	70	51	30	52 abc	67	80	73	—	69 bc
≥ 6	45	40	29	38 bc	—	100	40	53	53 c
$\bar{x}$[a]	70 a	58 a	36 a		80 ab	81 a	75 ab	63 b	

[a] Means by spray year within the same column, or row, followed by the same letter are not significantly different at $P = 0.05$.

[b] Dashes indicate insufficient sample size (< 25 plants) in this class.

ian vegetation along the west bank of a 9.7-km stretch of the Pecos River southeast of Artesia. Alkali sacaton (*Sporobolus airoides* Torr.), cottonwood (*Populus fremontii* S. Wats.), black willow (*Salix nigra* Marsh.), and various other herbaceous and shrub species will be planted as replacement vegetation after the approximately 2,000 ha of saltcedar are removed. Selected areas of standing dead saltcedar will be either burned by prescribed fire or roller chopped prior to replanting, while other areas will be left standing for comparison of revegetation methods. The project is funded federally by Congress with $400,000 designated for revegetation and for monitoring soil, water, and wildlife. The New Mexico Legislature appropriated $500,000 for saltcedar spraying and removal. In addition, about $100,000 of private money, or "services in-kind," has been donated by individual businesses.

This project resulted from an organized effort mostly representing soil conservation and irrigation districts in southeastern New Mexico. The group evolved into a nonprofit organization called the Pecos River Native Riparian Restoration Organization, whose efforts to educate the public and win support led to funding and project planning.

Small (< 1 ha) isolated cottonwood and black willow groves and open alkali sacaton meadows were designated for protection during herbicide spraying. A buffer area beneath and surrounding cottonwood groves was created by mechanically clearing saltcedar in autumn 1993. In summer 1994, resprouts were treated individually with imazapyr plus glyphosate at 0.5% plus 0.5% v/v plus 0.25% v/v nonionic surfactant with either backpack sprayers or a pickup-mounted sprayer. The power sprayer was outfitted with a 1,364-L tank, electric pump, and two 30-m hoses with handgun-type spray nozzles spraying at 50 psi.

In September 1995, a commercial agricultural aircraft applied imazapyr plus glyphosate at 0.84 plus 0.84 kg/ha in 65 L/ha total volume to a 1,214-ha area. The aircraft was fitted with a global positioning spray system, allowing the pilot to locate and exclude sensitive areas such as cottonwood groves and to create a 30-m buffer bordering the Pecos River. Spraying resulted in less than 5% saltcedar regrowth in targeted areas when evaluated 1 yr later. In September 1996, an additional 324 ha were aerially treated to complete the aerial application portion of the project. Individual plant treatment techniques using a pickup-mounte power sprayer applying imazapyr plus glyphosate at 0.5% plus 0.5% v/v were used to treat isolated plants within protected alkali sacaton meadows and saltcedar groves too small for aerial spraying.

Monitoring of wildlife populations within the PRNNRP area was initiated before saltcedar control and will continue throughout the 10-yr project. Wildlife surveys are being conducted by graduate students from New Mexico State University (Konkle 1996; Livingston 1996) to determine pre- and posttreatment small mammal, avian, and herpetofaunal use in dense saltcedar, open saltcedar, alkali sacaton, and mixed shrub–grassland communities. Water savings was a primary justification for removing saltcedar; thus, the water table beneath the PRNNRP area has been monitored monthly from ten 6.5-m-deep wells established in September 1992. To date, records indicate the spraying activities have had no effect on the normal cyclic drop or rise in depth to water during summer and winter months. These monitoring wells are also being used to test for herbicide residues, but none have been detected to this time.

Removal of saltcedar is a major aim for the PRNRP. However, it is only one step in the riparian restoration process along the Pecos River. Ultimately, the success of this project will not be totally judged by saltcedar ortality or by the success of revegetation efforts. Rather, future societal benefits will determine the project's ultimate success.

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